PRELIMINARY REGIONAL SEISMIC ANALYSIS OF NUCLEAR EXPLOSIONS AND EARTHQUAKES IN SOUTHWEST ASIA

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ABSTRACT

The recent nuclear test activity in Southwest Asia, beginning with India's announced nuclear tests on May 11, and 13, 1998, and ending with Pakistan's announced tests on May 28 and 30, 1998 provides new data for testing regional seismic discrimination algorithms that will be used to monitor compliance with the Comprehensive Test Ban Treaty. We collected seismograms from a number of earthquakes in Iran, Afghanistan, Pakistan, western India and the surrounding region that are recorded at regional and teleseismic distances by open seismic stations available through IRIS and other seismic data centers to compare with the nuclear test data. We are testing the most promising regional discriminants including P/S phase ratios, low/high frequency spectral ratios, high-P/ low-S frequency cross-spectral ratios, spectral coda peaking and regional Ms:mb on this dataset. Station NIL (Nilore, Pakistan), approximately 740 km from the India test site Haas excellent signal-to-noise ratios for regional phases from the May 11 Indian test and surrounding earthquakes. Preliminary results at NIL show excellent separation of the May 11 nuclear tests from earthquakes using Pn/Sn and Pn/Lg phase ratios at all frequencies tested (0.5-8 Hz). This result differs from most previous studies where P/S ratios show poor separation at low frequencies and improve as the frequency increases. Regional coda measures at NIL show the May 11 test has peaked spectra similar to other shallow tests which can also be used as a depth discriminant. Regional and teleseismic measures of Ms:mb also show good separation. We are also examining questions about yield and multiple sources determined from the seismic data. For example, we are comparing the 1998 nuclear tests with the 1974 Indian nuclear test at stations in common to examine relative amplitudes and signal content. Using NIL and an m_b=5.2 (NEIC) for the May 11 tests we place limits on the size of any seismic signal from the announced Indian tests on May 13 to m_b<2.8. We are still analyzing the data from this region and will present our latest results at the meeting.

Key Words: seismic, discrimination, identification, nuclear, India, Pakistan, Iran, Asia

OBJECTIVE

The objective of this work is to characterize the recent underground nuclear tests in Southwest Asia. These explosions provide new data to test discrimination and magnitude algorithms empirically in a new region, hopefully improving both the Comprehensive Test Ban Treaty (CTBT) monitoring capability in this area, as well as increasing our physical understanding of how these empirically developed seismic discriminant measures work when used in other regions.

RESEARCH ACCOMPLISHED

As part of the overall Department of Energy funded CTBT Research and Development program, LLNL is pursuing a comprehensive identification research effort to improve our capabilities to seismically characterize and discriminate potential clandestine underground nuclear tests from other natural and man-made sources of seismicity. Here we present preliminary magnitude, inferred seismic yield, signal character and discrimination results based on available open station regional and teleseismic data for the three seismic signals from announced underground nuclear tests in Southwest Asia and compared with nearby earthquakes.

Announced Tests and Data Availability

The surprise announcement of the detonation of an underground nuclear test on May 11, 1998 by the Indian government was the first declared nuclear explosion since China announced its testing moratorium in the summer of 1996 and the Comprehensive Test Ban Treaty (CTBT) was signed in September 1996 by 146 nations, though not by India and Pakistan. The Indian government announced a second test series on May 13th and the Pakistan government announced nuclear tests conducted on May 28 and 30, 1998. A summary of the announced tests and corresponding seismic information is given in Table 1. These tests generated three obvious seismic signals on May 11, 28, and 30 with magnitudes large enough to be clearly recognized at stations all over the world. These seismic signals are worthy of study for two reasons: first as discussed in the next section, there are inconsistencies between the announced tests and the seismic data; and second and most importantly, these explosions provide empirical data in a new region that can be used both to help calibrate the international CTBT monitoring network as well as to improve our understanding of the physical basis of the empirically developed regional discriminant algorithms so that they may be applied with confidence in regions where no nuclear test data is available for calibration.

The CTBT specifies an International Monitoring System (IMS) of seismic stations. The map in Figure 1 shows the planned IMS seismic stations in Southwest Asia along with the seismically determined locations of the recent tests and earthquakes from the USGS NEIC catalog. Unfortunately none of the planned IMS seismic stations in this region were installed at the time of these tests, severely limiting the availability of regional data. IRIS/IDA runs two stations, ABKT and NIL, near the sites of the IMS stations GEYT and PRPK. While ABKT data is does not appear to be available, NIL records of the Indian test were available through SPYDER shortly after the test. NIL has been running since December 1994 so the 1995-1997 earthquakes shown in Figure 1 indicate that there is plenty of available earthquake data available for comparison, including the large M_s=7.3 shallow thrust event (NEIC) near Quetta, Pakistan (29.9° N, 68.1° E) which has had a vigorous aftershock sequence. Unfortunately NIL appears to have been disconnected from the internet link prior to the Pakistan tests and no data from NIL for these tests is presently available. To examine the Pakistani tests we have turned to teleseimic data available through IRIS and the pIDC.

Magnitude, Inferred Yield and Signal Character

India conducted it's first nuclear test on May 18, 1974, in the same Rajasthan desert region as the more recent tests. The 1974 test generated a clearly detected teleseismic signal with m_b=4.9 (ISC, monthly PDE m_b=5.0). Because India conducted the 1974 explosion as a "Peaceful nuclear explosion" some data about it's emplacement have been reported (c.f. Chidambaram and Ramanna, 1975) such as the fact that it was a single explosion at depth of 107 m. However there is a large range in the yield stated by Indian scientists and officials for this event, from 2-12 kt (cf. Gupta and

Pabian, 1996). Using a published magnitude-yield formula from Murphy (1996) for well-coupled events in stable tectonic regions:

$$m_b = 4.45 + 0.75 \log(W), \qquad (1)$$

where W is yield and the usual factor of two uncertainty gives an inferred seismic yield of 2-8 kt for the 1974 event.

Twenty-four years later, on May 11, 1998 the government of India announced it had conducted its second, third and fourth nuclear tests at approximately 3:45 local time (10:15 GMT). In a news conference the next week Indian scientists provided more specific information including yields of 43, 12 and 0.2 kt (Burns, 1998) and that the two larger tests were separated by about a kilometer. A more recent report gives slightly different yields of 45, 15 and 0.2 kt (Marshall, 1998). Both reports agree the tests were conducted "simultaneously". Examination of the seismograms at teleseismic distances show a fairly simple impulsive P wave without any obvious signs of a multiple event, at least with any significant time delay between the shots. Examples of the Indian May 11 event are shown in Figure 2 at station WR1 in Australia, compared with other nearby events. Examination of the regional data at NIL also did not reveal any obvious spectral notches or other signs of source multiplicity. The event produced a $m_b = 5.2$ (weekly NEIC PDE) which using the above formula gives a yield range of 5-20 kt. Assuming simultaneous detonation of the three tests, the announced total yield of 55-60 kt appears to be at least three times larger than the inferred seismic yield. Because the emplacement conditions are not known it is possible that a cavity or substantial amount of porous material near the source could have reduced the coupling of energy into seismic waves, though this seems unlikely. Another explanation is that the yield announced by the Indian scientists are a factor of 3-6 times too large.

To examine the issue of relative source sizes and complexity we compared the May 11, 1998 tests with the May 18, 1974 single test at stations in common. Data from the 1974 test were obtained at YKA and EKA from the pIDC. Figure 3 shows a comparison of the seismograms at the YKR4 element with the smaller 1974 test scaled by a factor of about two to match the 1998 test amplitude. Note the remarkable similarity between the onset and overall character of these waveforms, again indicating no clear signs of source multiplicity. Some of the small differences apparent in the two waveforms may result from differences in the emplacement conditions, if they were similar we would expect a slight pulse broadening in the larger 1998 event because of it's larger expected elastic radius and hence lower corner frequency, but this is not apparent. We tried deconvoling the 1974 single event from the 1998 multiple event without successfully finding evidence of a multiple source. If the separation between the two larger events was only about a kilometer and the source were detonated within a tenth of second or so it probably would not be possible to resolve the separate sources with the available teleseismic data.

The scale factor at station YKA between the 1974 test and 1998 tests initially appeared larger than two when the nominal 1974 response was used. Recently Allison Bent (written communication) of the Canadian Geological Survey found the nominal 1974 YKA response was incorrect and the correct response puts the relative amplitude of the 1998/1974 tests at about two, in agreement with other stations and the overall m_b difference. For example at EKA the amplitude ratio between 1998 and 1974 appears to be about 1.6 based on data provided by Dr. Bowers and consistent with his own analysis (written communication). Using the factor of two relative amplitude difference between the 1974 and 1998 tests and the estimates of 2-12 kt for the 1974 test puts the May 11, 1998 cumulative yield at 5-30 kt, not too different from estimate the $m_b = 5.2$ estimates of 5-20 kt and still smaller than the announced yields. It would be most useful to find other stations in common between the 1974 and 1998 test to try to better understand the relative amplitude differences perhaps shedding some light on any differences in emplacement conditions between the two tests.

On May 13th India announced two additional "low yield tests" conducted simultaneously of 800 tons total yield (200 and 600 tons in Burns, 1998, 300 and 500 tons in Marshall, 1998). Examination of three hours of NIL data around the announced origin time fails to show any obvious seismic signal. Using an $m_b = 5.2$ for the May 11, 1998 signal, the largest amplitude in the three hour trace of seismic noise on May 13 gives an $m_b < 2.8$ corresponding to a well coupled yield less than 3-12 tons using formula 1 above. These tests were said to be conducted in a "sand dune" (Marshall, 1998) which might poorly couple the explosive energy into seismic waves. Murphy gives a modification of (1) for tests in dry alluvium, such as NTS tests above the water table, where the factor of 4.45 in (1)

is decreased by 0.75 to 3.75. Using this intercept gives a yield range less than 25-100 tons, still far lower than the estimate provided by the Indian scientists.

On May 28, 1998 Pakistan announced it had conducted its first five nuclear tests. One seismic signal is apparent and it has an m_b=4.8 (NEIC weekly PDE). Two days later on May 30th Pakistan announced another event, which had an m_b=4.6 (NEIC weekly PDE). Details on the yields, temporal and spatial separation of the six events has not been announced. As mentioned previously there is presently no regional data available for these events. Examination of teleseismic data at WB1 shows strong similarity between the two Pakistani test seismograms and the Indian test. Again the May 28th event does not show any obvious signs of source multiplicity. The tectonic setting for Indian and Pakistan events are fairly different with the Indian tests in a stable shield region and the Pakistani events in an active tectonic area behind the Makran subduction zone. Murphy (1996) gives a modification to (1) for an active tectonic region, like the western U.S. where the factor of 4.45 is reduced by 0.4 to 4.05. Using this modification gives total yield ranges of 5-20 kt for the May 28th events and 3-11 kt for the May 30th test. More work is needed to determine if the 0.4 "bias" factor between stable and tectonic regions is really the right number for the difference between the Indian and Pakistan test sites. If the bias were smaller, say 0.2, then these yield estimates decrease by a factor of 1.8. Correspondingly we report larger ranges for these events in Table 1.

Discrimination Tests

The regional seismic signals from the May 11, 1998 Indian test provide a new datapoint to test the performance of the most promising regional discriminants (e.g. Walter et al. 1995, Hartse et al. 1997) in an uncalibrated, untested region. Here we report preliminary results using several regional discriminant techniques.

Short-Period Regional Discriminants at NIL

The May 11, 1998 Indian nuclear test was recorded by the broadband station NIL (Nilore, Pakistan) at a distance of about 740 km. We gathered approximately 200 NIL recordings of regional earthquakes (distances 200-1500 km) to evaluate short-period regional discrimination of the Indian test. Earthquakes were selected from the NEIC-PDE, with reported depths less than 50 km and body-wave magnitudes in the range 3.6-6.0. The vertical component waveforms were previewed and the first arriving P-wave was picked. Pn, Pg, Sn and Lg phases were isolated with nominal group velocity windows. Amplitudes were measured in four frequency bands (0.5-8.0 Hz) from the smoothed amplitude spectrum of each phase. Figure 4 shows the vertical component seismograms of the Indian nuclear test and a nearby regional earthquake. The regional phase windows are shown.

Three classes of regional discriminants (amplitude ratios) were formed from the observed amplitudes: P/S amplitude ratios (e.g. Pn/Sn, Pn/Lg and Pg/Lg in the same frequency band), single phase spectral ratios (e.g. Pn [0.5-1 Hz] / Pn[4-8 Hz]) and cross-spectral ratios (e.g. Lg [1-2 Hz] / Pn [4-8 Hz]). Each discriminant was corrected for its distance trend. Figure 5 shows the distance corrected Pn/Lg (left) and Pn/Sn (right) amplitude ratios plotted at the low end of the frequency band. For this case, we only plot earthquakes which occurred to the south of NIL so that path effects not accounted for by removing the distance trend, such as Sn or Lg blockage potentially associated with the high topography, would not affect the discrimination results. Pn/Sn and Pn/Lg ratios separate the Indian test from the regional earthquakes, with the test having higher P/S ratios consistent with the absence of S-wave energy at the source. The separation is remarkably good for Pn/Sn and Pn/Lg even at the lowest frequency band (0.5-1.0 Hz). Pg/Lg amplitude ratios (not shown) do not separate the test from the earthquakes as well as Pn/Lg and Pn/Sn. Figure 6 shows the raw discriminant measures (no magnitude or distance correction) plotted as a function of distance (left) and of magnitude (right) for three classes of discriminants for all regional earthquakes and the Indian test recorded at station NIL. Removing the distance trend for the Pn/Lg ratios in the 4-8 Hz band improves the separation of the explosion from the earthquakes. Note that there is no magnitude trend for these data, indicating that forming the amplitude ratio in a fixed frequency band cancels the source effect. The phase spectral ratio, Pn[0.5-1 Hz] / Pn[4-8 Hz], and cross spectral ratio, Lg[1-2 Hz] / Pn[4-8 Hz] show strong distance trends. These spectral and cross spectral discriminants also show magnitude trends revealing a corner frequency scaling effect - smaller earthquakes have lower ratios than large earthquakes. Both these trends can be modeled and removed to enhance the separation of the Indian test and the earthquakes, though it is interesting to note that the scatter plot separation is pretty good even without any

corrections and including paths through much more complex topography and geology than that of the Indian test to NIL.

Regional Coda Source Spectra and Discriminants

We applied the regional coda methodology described in Mayeda and Walter (1996) to calibrate station NIL allowing the very accurate calculation of source spectra and magnitudes. Figure 7 shows the path and site corrected source spectra of a number of Indian and Pakistani earthquakes, with normal looking spectra that are flat at long period and rolloff approximately as $(frequency)^{-2}$ above the corner frequency. The Indian test in contrast shows a very peaked spectrum with a maximum near 1.5 Hz and a shallower rolloff at high frequencies. Peaked spectra are indicative of very shallow (<1 km) events as discussed in Mayeda and Walter (1996). We can use the coda derived spectra to calculate very accurate single station magnitudes such as MW(coda) from the low frequency level as well as mbLg or ML. A plot of Mw(coda) versus the NEIC mb values shows very good separation between the Indian explosion and surrounding earthquakes.

Regional Ms:mb measures

The May 11 Indian and may 28 and 30 Pakistani tests were large enough that the classic teleseismic discriminant Ms:mb can successfully discriminate these explosions from other earthquakes. We are developing regional Ms and mb scales in the Middle East and North Africa to extend the discrimination power of the Ms:mb method to much smaller events. Details of this work and a figure showing good separation using regional Ms measured at NIL are given in Pasyanos et al. (this volume).

CONCLUSIONS AND RECOMMENDATIONS

The three nuclear test seismic signals in Southwest Asia provide important new data to help calibrate seismic stations for improved monitoring of the CTBT. Regional data at NIL from the May 11, 1998 Indian test separates well from surrounding earthquakes using a variety of regional discriminants. Estimates of yield based on seismic magnitude and trace data are significantly smaller than statements by Indian scientists and officials to date. We recommend and plan to conduct more research to further characterize these events, particularly as more seismic data and information on emplacement conditions becomes available.

References

Burns, J. F. "Indian scientists confirm they detonated a hydrogen bomb", in the *New York Times*, May 18, 1998.

Chidambaram, R. and R. Ramanna, Some studies on India's peaceful nuclear explosion experiment, in *Peaceful Nuclear Explosions IV: Proceedings of a technical committee on the peaceful uses of nuclear explosions organized by the International Atomic Energy Agency*, pages 421-436, January 20-24, 1975,.

Gupta, V. and F. Pabian, Investigating the allegations of Indian nuclear test preparations in the Rajasthan desert, *Science and Global Security*, 6, xx-yy, 1996.

Hartse, H., S. R. Taylor, W. S. Phillips, and G. E. Randall, (1997). A preliminary study of regional seismic discrimination in Central Asia with an emphasis on Western China, *Bull. Seism. Soc. Am.* **87**, 551-568.

Marshall, E. "Did test ban watchdog fail to bark?", in *Science*, **280**, pages 2038-2040, June 26, 1998.

Mayeda, K. M. and W. R. Walter, Moment, energy, stress drop and source spectra of Western U.S. earthquakes from regional coda envelopes, *J. Geophys. Res. 101*, 11,195-11,208, 1996.

Murphy, J. Types of seismic events and their source descriptions, in Monitoring a *Comprehensive Test Ban Treaty*, editors E. S. Husebye and A. M. Dainty, Kluwer Academic Publishers, Dordrecht, 1996, pages 225-246.

Walter, W. R., K. Mayeda, and H. J. Patton (1995). Phase and spectral ratio discrimination between NTS earthquakes and explosions Part 1: Empirical observations, *Bull. Seism. Soc. Am.*, **85.**, 1050-1067

Table 1.*

Date	Annouced Time	Seismic time	Anounced Yield (kt)	Seismic m_b	Seismic Yield (kt)
5/18/74		02:34:55.4	2-12	4.9 (ISC)	2-8
5/11/98	10:15:05.7	10:13:42.0	55.2 (43+12+0.2)	5.2(NEIC)	5-20
5/13/98	06:21:00.0	No Detection	0.8 (0.6+0.2)	2.8(max)	<0.1
5/28/98		10:16:15.2	-	4.8(NEIC)	3-20
5/30/98		06:54:54.9	-	4.6(NEIC)	2-11

*See text for details, seismic yields inferred from Murphy (1996) m_b-yield formulas
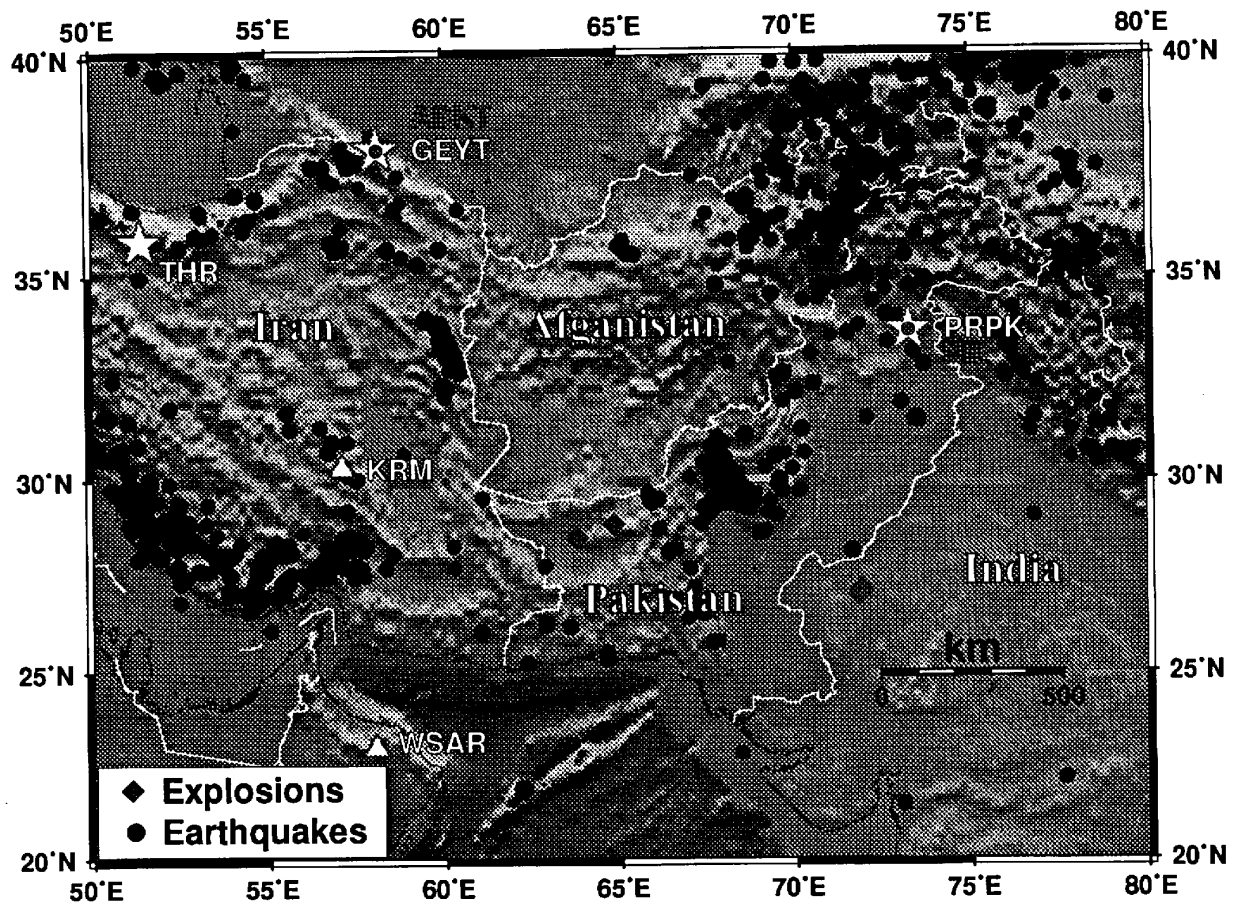
Fig. 1. Topographic map showing seismic locations of 1974 and May 11, 1998 Indian nuclear tests, the May 28, and 30, 1998 Pakistani nuclear tests and earthquakes from the PDE catalog for 1995-1997. Also shown are planned locations of IMS primary (stars) and auxilary (triangle) seismic stations and the nearly co-located IRIS/IDA stations ABKT and NIL.
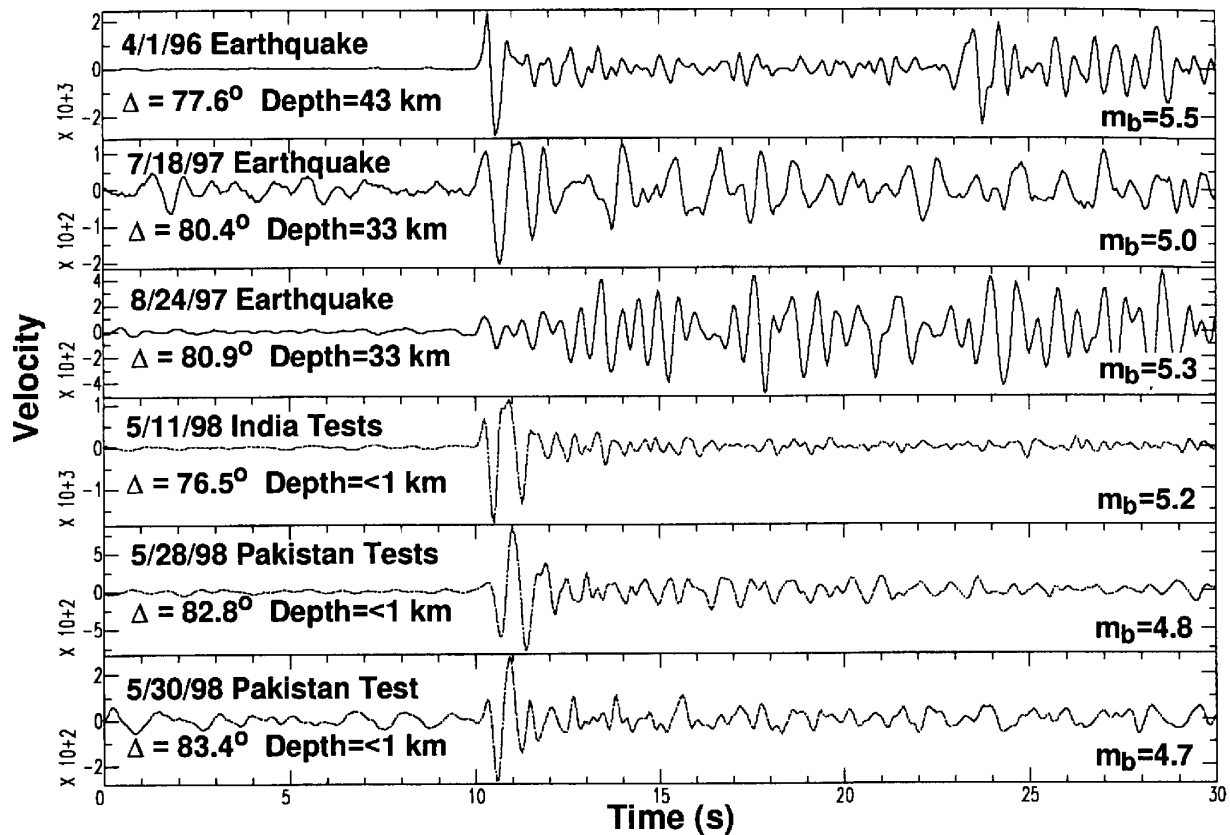
Fig. 2. Comparison of three Pakistan earthquakes with the three nuclear test signals at the same station, WR1, an element of the Warramunga array in northern Austrailia. The short period records were aligned on first motion and bandpass filtered between 0.5 and 8 Hz.
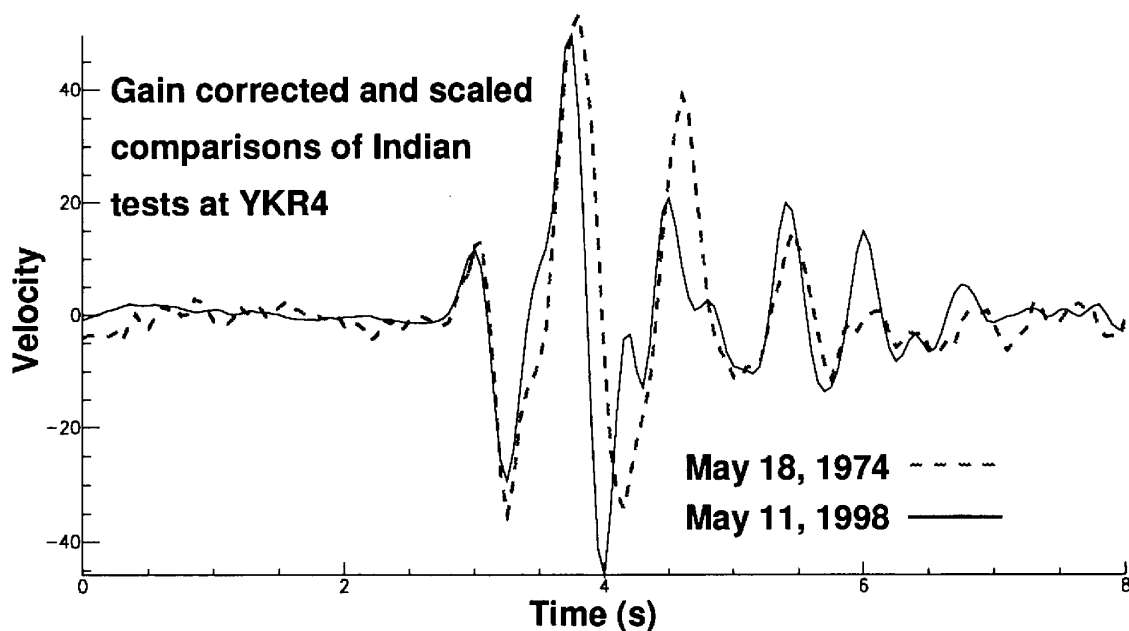

Fig. 3. A comparison of the 1974 and 1998 underground nuclear tests at a common element of the Yellowknife array in northern Canada. The 1974 test has been scaled by an amplitude factor of ~2.
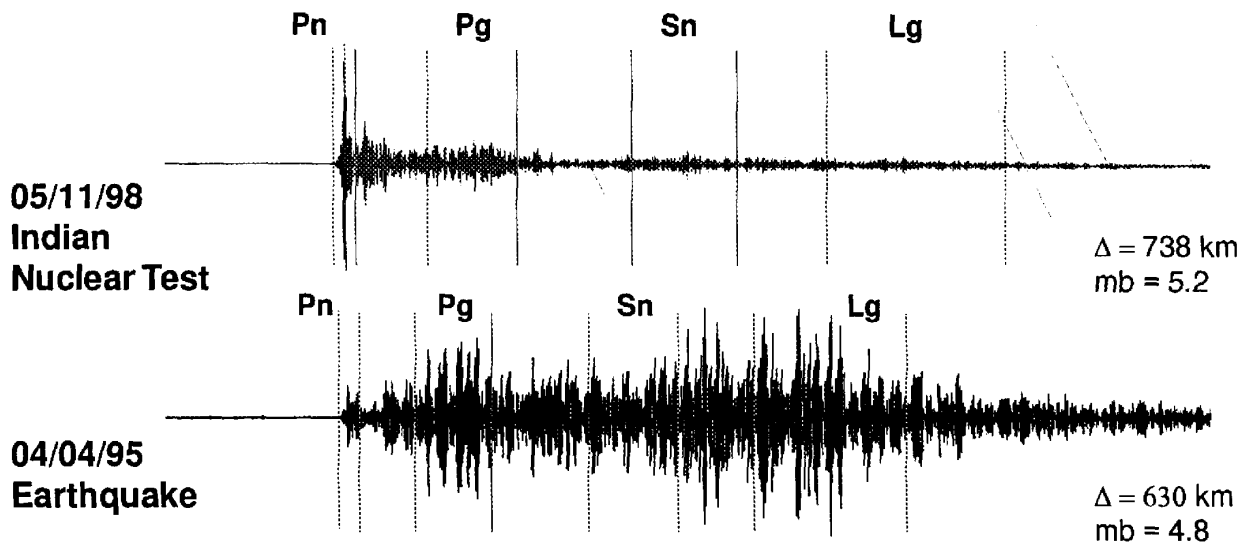
Fig. 4. Seismograms of the Indian nuclear test (top) and a nearby earthquake (bottom) recorded at station NIL (Nilore, Pakistan). Each recording was filtered 2-4 Hz. The phases Pn, Pg, Sn and Lg are isolated by the vertical lines. Note that Pn is strong relative to Sn and Lg for the explosion, but the opposite is the case for the earthquake.
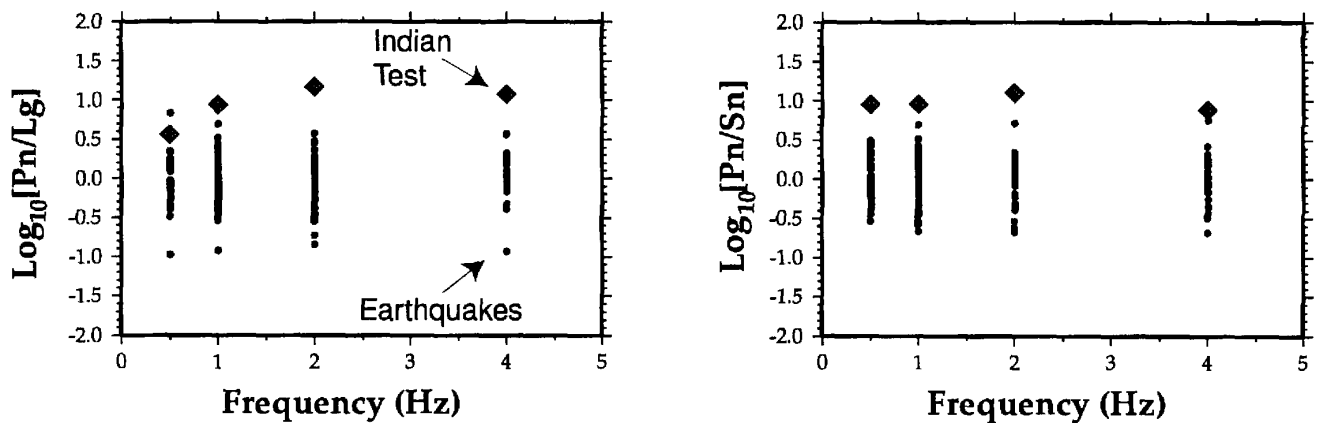

Fig. 5. Pn/Lg (left) and Pn/Sn (right) amplitude ratios versus frequency for the Indian nuclear test (diamond) and nearby earthquakes (circles). Only earthquakes from the south of NIL were included in this figure to avoid possible path effects such as Sn or Lg blockage. Note that the P/S ratios are higher for the Indian test than for the earthquakes and they provide good separation of the two source types for all frequencies.
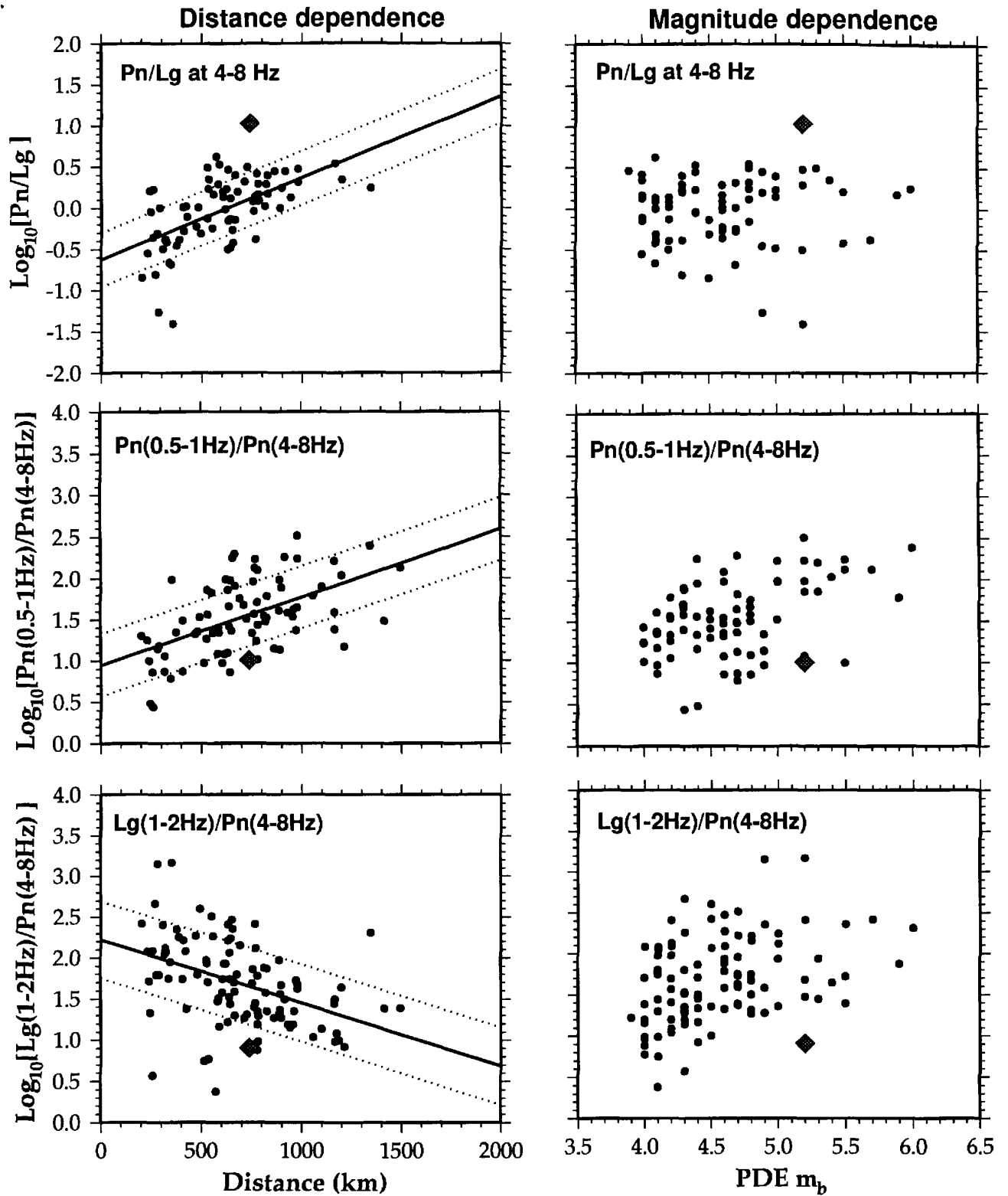
Fig. 6. Raw discriminant amplitudes (no magnitude or distance corrections applied) as a function of distance and magnitude at NIL for three discriminants: a 4-8 Hz Pn/Lg phase ratio (top row), a 0.5-1Hz/4-8 Hz Pn spectral ratio (middle row) and a 1-2Hz Lg / 4-8 Hz Pn cross-spectral ratio (bottom row). Indian explosion is denoted as a diamond. All regional earthquakes with S/N>2 shown as circles.
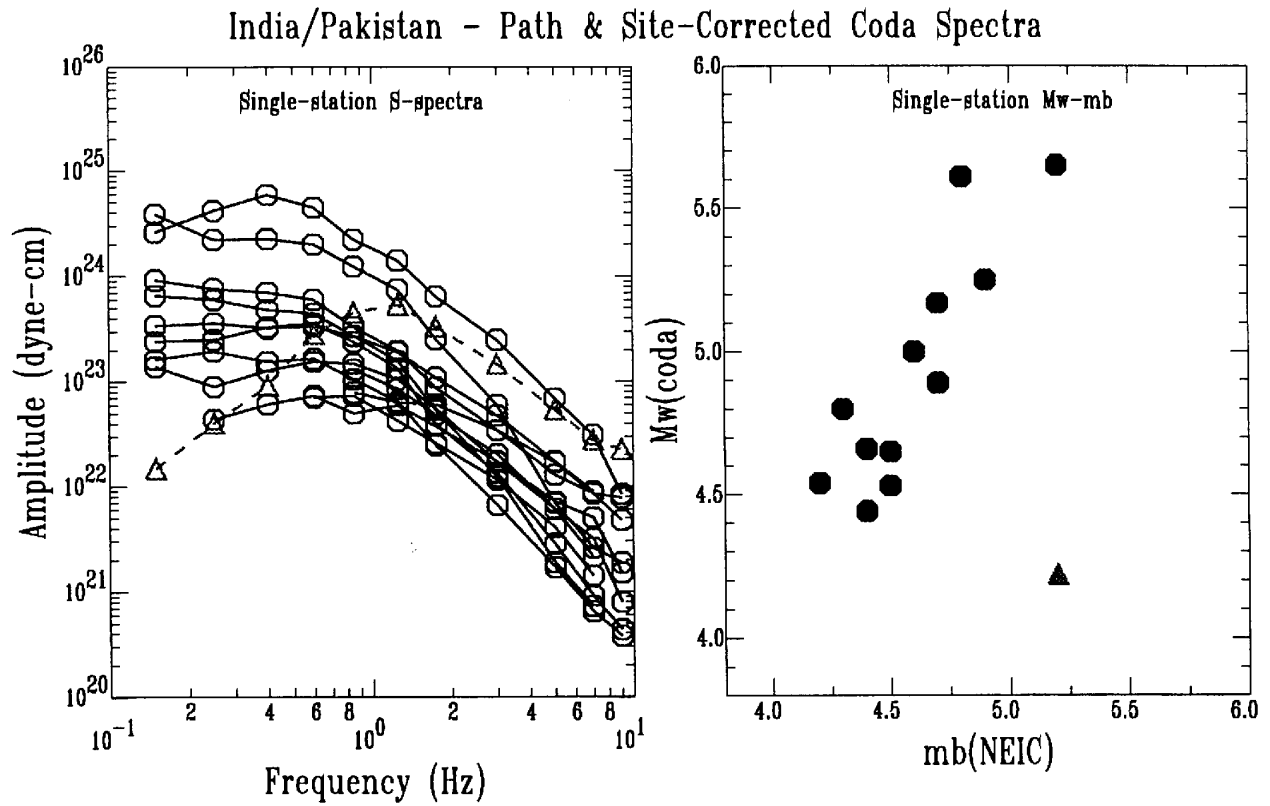
Fig. 7. Regional coda determined source spectra at NIL for events in India and Pakistan. The May 11, 1998 Indian test spectra (triangles) looks anomalous compared to the earthquakes (circles), showing strongly peaked spectra characteristic of very shallow sources (Mayeda and Walter, 1996). Using the low frequency level to obtain M_W(coda) plotted as a function of the NEIC m_b provides good discrimination between the Indian test and surrounding earthquakes.